Skimming through Saturn's Atmosphere: The Climax of the Cassini Grand Finale Mission

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On September 15, 2017, the long-lived Cassini Mission to Saturn came to a triumphant end as the Cassini orbiter plunged deep into Saturn's atmosphere, all the while transmitting engineering and science data back to Earth before Saturn's atmosphere destroyed the orbiter. Even before the final plunge, the Cassini spacecraft became the first spacecraft to successfully skim Saturn's atmosphere and collect atmospheric data during its final five complete orbits around Saturn (Rev-288 through Rev-292). During those five final orbits, the spacecraft was flying in Reaction Control Subsystem (RCS) control in order to maintain greater control authority. Therefore, by analyzing the thruster on-time flight data telemetered back to Earth after each orbit, atmospheric density estimates can be extracted. This paper proposes a method of using Cassini Attitude Control Flight Data to reconstruct Saturn atmospheric density profiles for each of the five final orbits around Saturn.

Acronyms

AACS	=	Cassini Attitude and Articulation Control Subsystem
ASI	=	Italian Space Agency
CM	=	Center of mass
ERT	=	Earth Receive Time
ESA	=	European Space Agency
HGA	=	High Gain Antenna
LOS	=	Loss of Signal
ME	=	Main Engine
NASA	=	National Aeronautics and Space Administration
OTM	=	Orbit Trim Maneuver
PDT	=	Pacific Daylight Time
RCS	=	Reaction Control Subsystem
RWA	=	Reaction Wheel Assembly
S/C	=	Spacecraft
SCET	=	Spacecraft Event Time
SCO	=	Cassini Spacecraft Operations Team
SOI	=	Saturn Orbit Insertion
TCM	=	Trajectory Correction Maneuver
UTC	=	Coordinated Universal Time

I. Introduction – Synopsis of the Cassini Mission to Saturn

A. Overview of Cassini Mission

THE Cassini-Huygens mission was a collaborative effort between the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the Italian Space Agency (ASI). Cassini-Huygens was launched in October 1997 onboard a Titan IVB/Centaur, and followed a "VVEJGA" trajectory, using gravity assists from two Venus flybys, one Earth flyby, and one Jupiter flyby before arriving at Saturn.[1] After travelling a total distance of 3.5 billion km (~ 2.2 billion mi) the spacecraft entered Saturn's orbit on July 1, 2004 PDT. Once in orbit, the Cassini spacecraft deployed the 320 kg ESA-built Huygens probe into the atmosphere of the moon Titan

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before beginning its study of the Saturnian system via its diverse suite of "remote sensing" and "in-situ" instruments.[1] The Cassini program was granted two mission extensions; the second and final extension, named the "Solstice Mission", was slated to end in September of 2017.[2] Cassini used two separate supplies of onboard fuel, monomethylhydrazine and nitrogen tetroxide for the main engine (ME) and hydrazine for the thruster control system.[1] By the end of the Solstice mission both fuel supplies were running low, making a third mission extension impossible.[2] On September 15, 2017, Cassini was purposely flown on an impact trajectory deep into the harsh atmosphere of Saturn. During its final plunge, the spacecraft transmitted unique science data of Saturn's atmosphere back to Earth. Within minutes of entering Saturn's atmosphere, the attitude control system was overwhelmed by Saturn's atmospheric torque. Consequently, the spacecraft tumbled and ultimately was destroyed. At the end of its life, Cassini had accumulated nearly 20 years of spaceflight, with over 13 of those years being spent conducting demanding science campaigns.[2]

B. The Architecture of Cassini's Proximal Orbits Phase

On April 22, 2017 Cassini successfully completed its final targeted Titan flyby, deemed T-126, with a closest approach altitude of 979 km. The gravitational effects of T-126 adjusted Cassini's trajectory so that each subsequent orbital periapsis would fall within the gap between Saturn and its rings. This final phase of the Cassini mission, also known as the "Proximal Orbits" phase, was designed to fly 22 orbits between the innermost D-ring and the top of Saturn's atmosphere.[3] The D-ring is diffuse, and it was not certain how far down towards Saturn's cloud tops the D-ring particles would reach. At the time of planning these D-ring orbits, the latest ring models suggested there was low likelihood of Cassini colliding with D-ring particles during the Proximal Orbits. Still, the Proximal Orbit D-ring crossings were the most dangerous faint ring crossing because any particles encountered during the crossings would be traveling at velocities exceeding 30 km/s relative to Cassini. [3] After T-126 there were no more targeted Titan flybys, but there were nine more non-targeted Titan flybys. Additionally, the final orbit trim maneuver (OTM) was performed on July 15, 2017 after which the spacecraft was on a purely ballistic trajectory that would ensure the spacecraft would crash into Saturn in September regardless if the Cassini ground team lost its ability to communicate with the spacecraft.[2]

Prior to the final plunge, the spacecraft completed five full orbits with periapses that skimmed Saturn's upper atmosphere. These orbits provided the first in-situ Saturn atmospheric data ever collected by a space probe and gave a preview of what the atmosphere would be like during the final plunge. A major concern with the final five orbits was that the atmospheric torque might overwhelm the spacecraft's small thruster torque. Since no previous spacecraft had flown anywhere near Saturn's atmosphere, the atmospheric density was uncertain. Using remote measurements, Cassini scientists developed models that predicted the atmospheric density for a given periapsis altitude. These models were used to design the nominal closest approach altitudes the spacecraft could safely fly for each of the final five orbits.

On September 11, 2017 the spacecraft completed its final non-targeted Titan flyby, which robbed the spacecraft orbit of just enough energy so that instead of falling within the clear gap between the planet and the rings, the periapsis on September 15, 2017 would now plunge deep enough into the atmosphere to ensure disposal.[2]

II. The Cassini Spacecraft

Cassini was a 3-axis stabilized spacecraft with an 11-meter magnetometer boom and three 10-meter Radio and Plasma Wave Science (RPWS) antennas (Fig.1).[4] Cassini had a body-fixed 4-meter diameter High Gain Antenna (HGA) parabolic reflector dish for telecommunications. At launch, the total spacecraft mass was 5,560 kg of which 3,000 kg was liquid bi-propellant and 132 kg was hydrazine.[2]

A. The Reaction Control Subsystem (RCS)

The Cassini orbiter was equipped with two separate subsystems used for delta-V maneuvers, including OTMs, Trajectory Correction Maneuvers (TCMs), and Saturn Orbit Insertion (SOI). The Cassini team used the bi-propellant main engine for large delta-V maneuvers, and the Reaction Control Subsystem (RCS) thrusters for small (<0.3 m/s) delta-V maneuvers. The RCS subsystem was composed of four hydrazine thrusters aligned with the spacecraft ±Y-axes and four hydrazine thrusters along the S/C –Z-axis. When the spacecraft was performing a delta-V maneuver with the RCS subsystem, only the four Z-facing thrusters contribute to the delta-V.[5,6]

In addition to small delta-V maneuvers, the RCS subsystem also doubled as one of two attitude control subsystems.[4] When the spacecraft was under RCS attitude control, onboard flight software off-pulsed all eight active RCS thrusters (Fig. 2). The four thrusters aligned with the S/C ±Y-axes fired as couples (Y1-Y3 fired as one pair, and Y2-Y4 fired as another pair). Since both thrusters in a pair were balanced with each other, a Y-thruster pair fired without imposing a net delta-V on the spacecraft. Rather, a Y-thruster pair provided a purely rotational control torque about the Z-axis. The four thrusters aligned with the –Z-axis fired independently of each other and were used for X and Y-axis rotational control. When any of the four Z-facing thrusters fired, they impart both a net delta-V and a control torque on the spacecraft.[5,6]

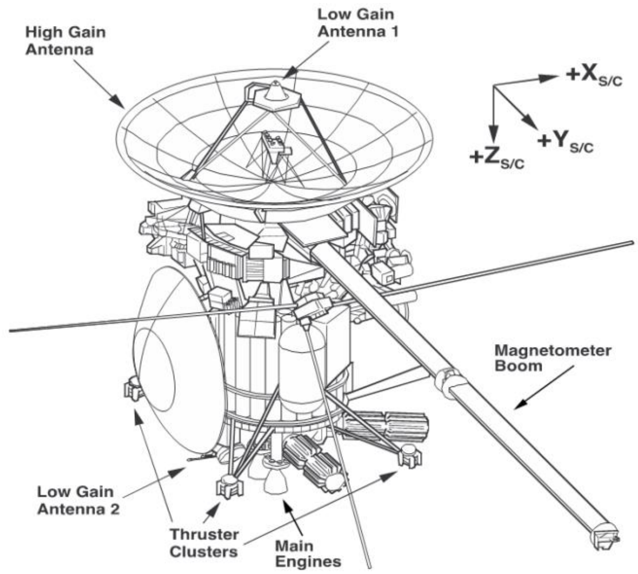

Figure 1. Overview of Cassini spacecraft.

B. The RWA Control Subsystem

The spacecraft also had a Reaction Wheel Assembly (RWA) control subsystem, which was independent of the RCS control subsystem. RWA control was typically preferred because it improved pointing accuracy and stability, while also conserving hydrazine.[1] However, the RWAs had much lower control authority than the RCS thrusters, which meant that for low Titan atmosphere flybys, the final five Saturn orbits, and the final plunge, the spacecraft had to fly in RCS control to ensure adequate control authority in the presence of atmospheric torques that would overwhelm the RWAs. The scope of this paper is limited to analyzing flight data while the spacecraft operated in RCS control during the Saturn atmospheric flybys.

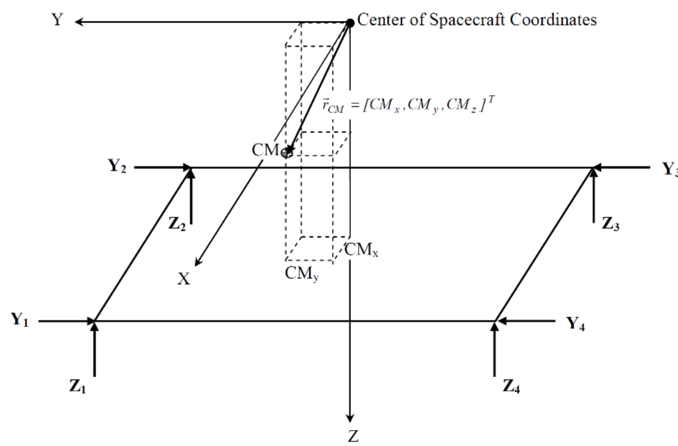

Figure 2. Thruster layout of reaction control subsystem on Cassini.

III. The Importance of Saturn Atmospheric Density Estimates for the Cassini Mission

Accurately estimating the composition and density of Saturn's atmosphere was a high priority for the Cassini scientists. The in-situ data collected during the final five orbits and the plunge gave the science community its first direct compositional measurements of Saturn's atmosphere, and the data will be analyzed for years to come. However, during the execution of the final five orbits, atmospheric density calculations were also highly valuable from a spacecraft safety and mission assurance perspective. If the atmospheric density encountered in any of the final five orbits was "too high" (this threshold will be defined later), then the RCS control subsystem would be overwhelmed by the atmospheric torque and the spacecraft would tumble.

As mentioned in the previous section, the nominal periapsis altitudes for each of the five Saturn-skimming orbits were determined from predictive atmosphere models based on remote instrument measurements. Note that since Saturn is a gas giant, with no observable solid surface, the closest approach altitude was defined as the distance the spacecraft flew above the radius at which atmospheric pressure was equivalent to 1-bar (Earth's atmospheric pressure at sea level). Also, note that since Saturn is highly oblate, the closest approach "altitude" did not correlate with periapsis (which is measured from Saturn's center). Table 1 shows the predicted peak duty cycles for each of the five final orbits (revolutions) that skimmed Saturn's atmosphere.

Table 1. Predicted Peak Duty Cycles for Rev288-Rev292

Rev	Periapsis Date	Minimum Altitude km	Y-Thrusters %	Z-Thrusters %
288	14 August 2017	1706	9.25	4.39
289	20 August 2017	1652	11.65	21.00
290	27 August 2017	1626	14.96	7.51
291	2 September 2017	1639	13.95	6.75
292	9 September 2017	1675	12.33	7.64

The table above lists the predicted mean peak duty cycles for the spacecraft Y-thruster pairs and the mean peak duty cycles for the spacecraft Z-thrusters. Note that these predicted duty cycles were generated prior to the first Saturn atmosphere orbit (Rev 288) and were produced by atmosphere models built purely with remote instrument measurements. No in-situ atmospheric measurements had been obtained at the time of generating the above predicts.

A. The Contingency Pop-Up/Pop-Down OTM Strategy

As was previously stated, on July 15, 2017 Cassini performed OTM-472 that restored the spacecraft back to the reference trajectory. After that final OTM the spacecraft flew a completely ballistic trajectory, which ended in the final plunge. However, at the time of performing OTM-472 the Cassini team had not received any in-situ atmospheric data since the first Saturn-skimming orbit would not be until August 14, 2017 (Rev-288). The Cassini team anticipated the likely possibility that the actual Saturn atmosphere could be significantly different from what was predicted by the models. One possibility was that the spacecraft would fly the final five orbits at the nominal altitude and would discover that the atmosphere was much thinner and contracted than anticipated. This would be acceptable from a spacecraft safety point of view, but would be detrimental from a scientific point of view, because the onboard in-situ science instruments would not be able to sense a strong atmospheric signal. The other possibility was that the spacecraft would attempt to fly the final five orbits at the nominal altitude but would discover that the atmosphere was much denser and extended higher than anticipated. This would cause the spacecraft thrusters to be overwhelmed by the atmospheric torque and the spacecraft would tumble and go into safe-mode.

To account for these two possible scenarios, the Cassini team developed a "contingency pop-up/pop-down OTM strategy" that would rely on thruster duty cycle data and atmospheric density derived from thruster on-time flight data to determine how thick the atmosphere was in the first orbit (Rev-288). Thruster duty cycle is defined by Eq. (1) and is a measure of how much a thruster has to fire during a defined time interval in order to counter the atmospheric torque. By definition, the S/C thruster duty cycles can only reach 100% before the S/C is overwhelmed by atmospheric torque and loses attitude control. Based on this analysis the subsequent orbit altitudes would be raised with a "pop-up" OTM or lowered with a "pop-down" OTM. Prior to Rev-288, the Cassini team agreed that a pop-down or pop-up maneuver would be considered if the Rev-288 duty cycles came in below 10% or above 60%, respectively.

$$Duty\ Cycle\ \% = 100 * \frac{thruster\ ontime(t_k) - thruster\ ontime(t_0)}{t_k - t_0}\ for\ time: t_k > t_0 \geq 0 \tag{1}$$

After the spacecraft completed Rev-288, it turned its high-gain antenna back to Earth and downlinked the highly anticipated flight data that would reveal Saturn's atmosphere for the first time. The highest duty cycle the models predicted for Rev-288 was 9.25% (see Table 1). However, flight data revealed that the highest duty cycle had actually been closer to 30%, which indicated that Saturn's atmospheric density for Rev-288 had been approximately 3 times higher than the models had predicted. This was a welcome surprise for the Cassini team because it meant that the actual atmosphere was thicker than originally anticipated, to the point where our science instruments would collect good science data and our thrusters would comfortably maintain control authority. This duty cycle analysis was repeated after each of the subsequence four Saturn-skimming orbits to ensure the safety of the spacecraft until the final plunge. The Cassini mission was completed successfully without the need to implement neither the pop-up nor pop-down contingency maneuver. Table 2 summarizes the actual peak duty cycles for each of the five final orbits (revolutions) that skimmed Saturn's atmosphere.

Table 2. Actual Peak Duty Cycles for Rev288-Rev292

Rev	Periapsis Date	Minimum Altitude km	Y-Thrusters %	Z-Thrusters %
288	14 August 2017	1706	29.7	10.9
289	20 August 2017	1652	33.3	44.0
290	27 August 2017	1626	40.6	15.0
291	2 September 2017	1639	41.0	14.5
292	9 September 2017	1675	25.8	9.5

The table above lists the actual mean peak duty cycles for the spacecraft Y-thruster pairs and the mean peak duty cycles for the spacecraft Z-thrusters. Note that these duty cycles were generated from thruster on-time flight data transmitted back to Earth after each periapsis.

IV. Overview of Density Reconstruction Method Using Thruster On-Time Flight Data and Accumulated Angular Momentum

There are several independent methods of atmospheric reconstruction that use different sources of flight data. The onboard Ion and Neutral Mass Spectrometer (INMS) instrument was an instrument that could collect in-situ samples of the atmosphere the spacecraft was flying through and determine the chemical, elemental, and isotopic composition of the particles in the atmosphere.[7] A second density reconstruction method uses radiometric Doppler data to determine shifts in the spacecraft's orbit. These shifts in orbit can be attributed to an atmospheric drag force, which can then be converted to a corresponding atmospheric density.[6] A third method of atmospheric density relies on thruster on-time flight data and additional attitude control subsystem telemetry, as well as the principle of conservation of angular momentum. This third method of reconstruction was originally developed for Titan atmospheric density reconstructions, but with some slight modifications, it can be applied to the Saturn-skimming orbits (Rev-288 through Rev-292). The thruster-based atmospheric density reconstruction method has been developed in detail in Ref. 5 and Ref. 8 but will be summarized in the following section.

A. Standard Atmospheric Torque Equation

The method of estimating atmospheric density based on conservation of angular momentum and thruster on-time flight data essentially requires that thruster data be used to estimate a curve of accumulated angular momentum. From the slope of the angular momentum curve, an estimated atmospheric torque curve can be derived. Finally, from that atmospheric torque curve, an atmospheric density can be extracted. For this method to accurately estimate torque and density, good estimates of the velocity, thruster on-times, thruster moment arms, the center of mass and other parameters must be obtained. In particular, an accurate estimate of the spacecraft's "center of pressure" is required for the calculation. Note that the center of pressure is defined as the point where the net atmospheric force can be treated as a single vector.[8]

The relationship between S/C orientation and motion, and atmospheric torque and density is given by Eq. (2).

$$\vec{T}_{Atm} = \frac{1}{2} C_D \rho V^2 A_{Proj} \hat{u}_V \times (\vec{r}_{CP} - \vec{r}_{CM}) \tag{2}$$

where:

$\vec{T}_{\mathrm{Atm}}$	=	atmospheric torque, Nm
$\mathrm{C_D}$	=	drag coefficient, dimensionless
ρ	=	atmospheric density, kg/m^3
V	=	magnitude of the spacecraft velocity relative to the rotating Saturn, m/s
$\mathrm{A_{Proj}}$	=	spacecraft projected area, m^2
$\hat{\mathrm{u}}_{\mathrm{V}}$	=	unit vector of spacecraft velocity expressed in spacecraft body frame
$\vec{\mathrm{r}}_{\mathrm{CM}}$	=	position vector of the spacecraft's center of mass relative to the origin of the spacecraft coordinate frame, m

$\vec{r}_{CP}$ = position vector of the spacecraft's center of pressure relative to the origin of the spacecraft coordinate frame, m

Equation (2) can be solved for atmospheric density as shown in Eq. (3). Equation (3) has three components and produces density estimates based on Cassini body and orientation-relative data for each of the three spacecraft body axes, assuming all other parameters are accurately known.

$$\rho = \frac{2\vec{T}_{Atm}}{C_D V^2 A_{Proj} \hat{u}_V \times (\vec{r}_{CP} - \vec{r}_{CM})} \tag{3}$$

The drag coefficient has been estimated using formulae in Ref. 9. In our work, we assume C_D = 2.1 ± 0.1. This is a reasonable drag coefficient value when compared with results determined using orbital data of Earth-orbiting satellites.[10] The velocity vector magnitude of the spacecraft relative to Saturn is accurately determined by Cassini navigation trajectory reconstruction. It is accurate to about 5 m/s one-sigma. The velocity unit vector in the spacecraft body frame is based on onboard attitude knowledge accurate to about 0.1 mrad. Center of mass is estimated via propellant accounting and ground software and has been confirmed by radiometric means.[6] $\vec{T}_{Atm}$, A_{Proj}, and $\vec{r}_{CP}$ are less accurately known, and are the dominant sources of error in the thruster on-time reconstruction method. Ref. 6 theorizes that the uncertainty in center of pressure may cause the thruster-based reconstruction method to overestimate density by an upper bound of up to 30% depending on the spacecraft's orientation during the atmospheric flyby.

B. Estimating Atmospheric Torque in the Thruster On-Time Reconstruction Method

The key to torque estimation is the "accumulation" of angular momentum over time. The slope of this curve is the atmospheric torque. In most atmospheric flybys, a component of the atmospheric torque is applied around each of the three spacecraft body axes. To reconstruct density, it is convenient to select the dominant spacecraft axis that contains most of the atmospheric torque. This assumption essentially decouples the spacecraft axes and allows us to select about which axes we perform the density reconstruction.[8]

The accumulated angular momentum curve that is calculated from raw thruster on-time flight data is noisy, and this noise is magnified when we take the derivative of angular momentum to obtain torque. Therefore, prior to taking the derivative, two hyperbolic tangent functions are used to curve-fit the angular momentum curve.[8] This approach provides a smooth momentum curve that is suitable for differentiating. Due to the symmetry of the hyperbolic tangent functions, this approach requires both inbound and outbound flight data to match the symmetry of the functions. In other words, this method assumes the analyst has obtained data during the spacecraft's atmospheric approach as well as during its atmospheric departure. This means that this method of density reconstruction cannot be applied to Cassini's final plunge since the spacecraft entered the atmosphere but did not leave it, effectively breaking the symmetry assumed by the hyperbolic tangent functions. Figure 3 shows the accumulated angular momentum and curve-fitted momentum curves obtained from the thruster on-time data from the August 14 Rev-288 orbit. Figure 4 is a zoomed in version of Fig. 3 that emphasizes the noisy nature of the raw angular momentum curve.

Differentiating the curve-fitted angular momentum curve results in a smooth curve of atmospheric torque about the dominant z-axis of the spacecraft. Note that unlike Titan atmospheric reconstructions, the Saturn atmospheric reconstruction produces an atmospheric torque curve that is offset from the time of periapsis due to the oblateness of Saturn. The torque curve in Fig. 5 provides the final parameter of Eq. 3 which is $\vec{T}_{Atm}$. Using Eq. 3 and the thruster on-time method as described in Ref. 8 a profile of atmospheric density can be plotted for Rev-288, Rev-289, Rev-290, Rev-291, and Rev-292 each of which resulted in inbound/outbound flight data. Density reconstruction results and duty cycle profiles based on thruster flight data are presented in section V.

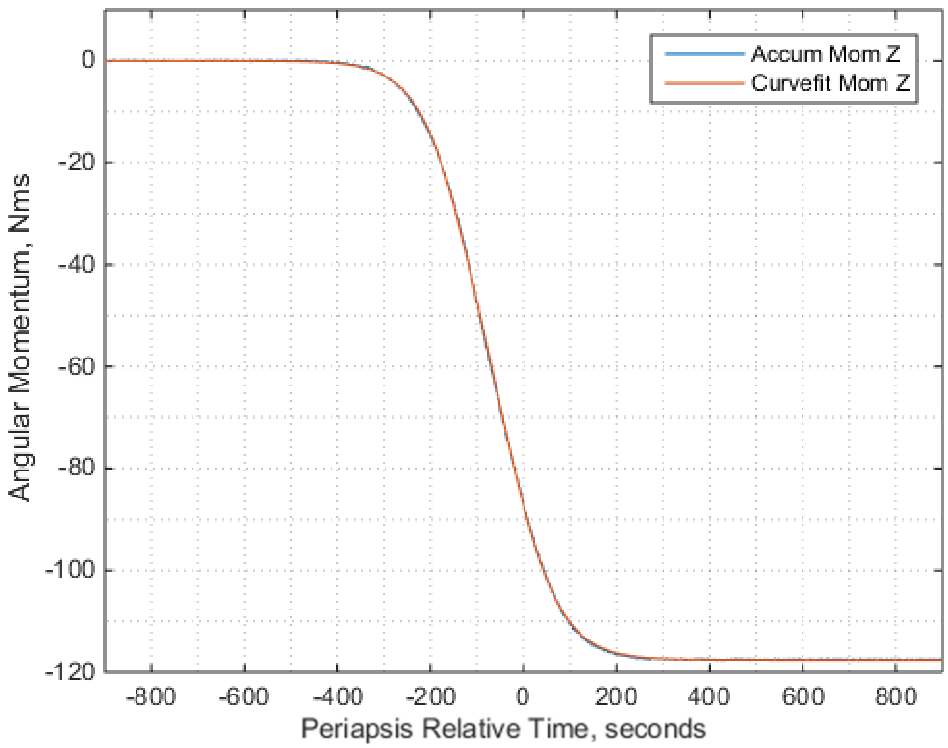

Figure 3. Rev-288 accumulated angular momentum about S/C Z-axis

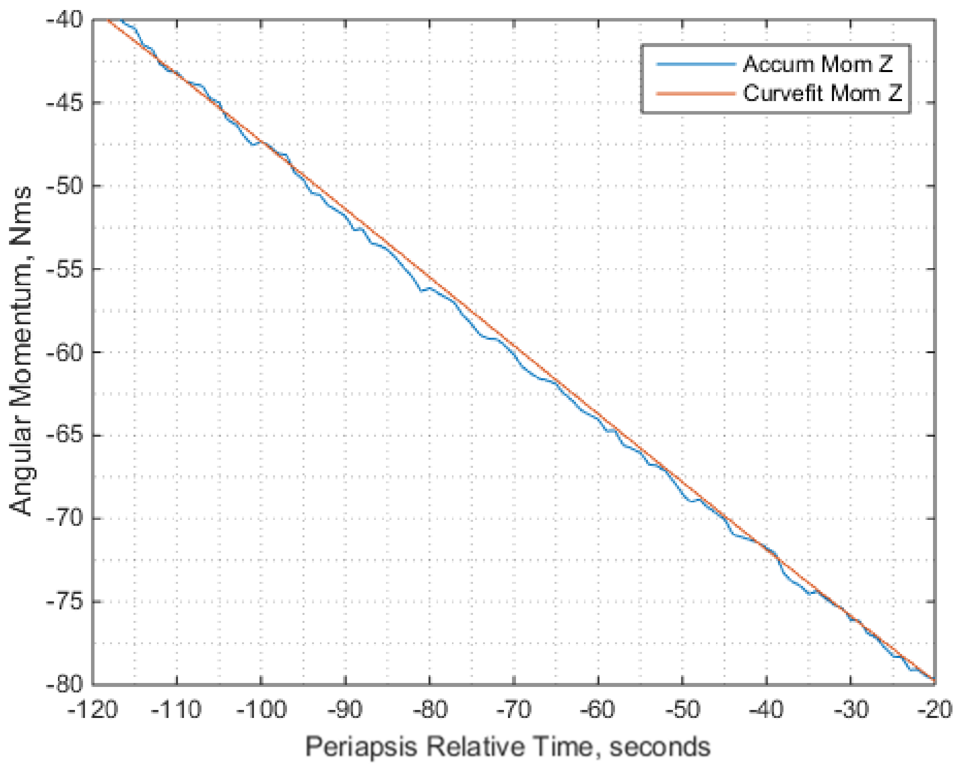

Figure 4. Rev-288 accumulated angular momentum about S/C Z-axis (zoomed-in)

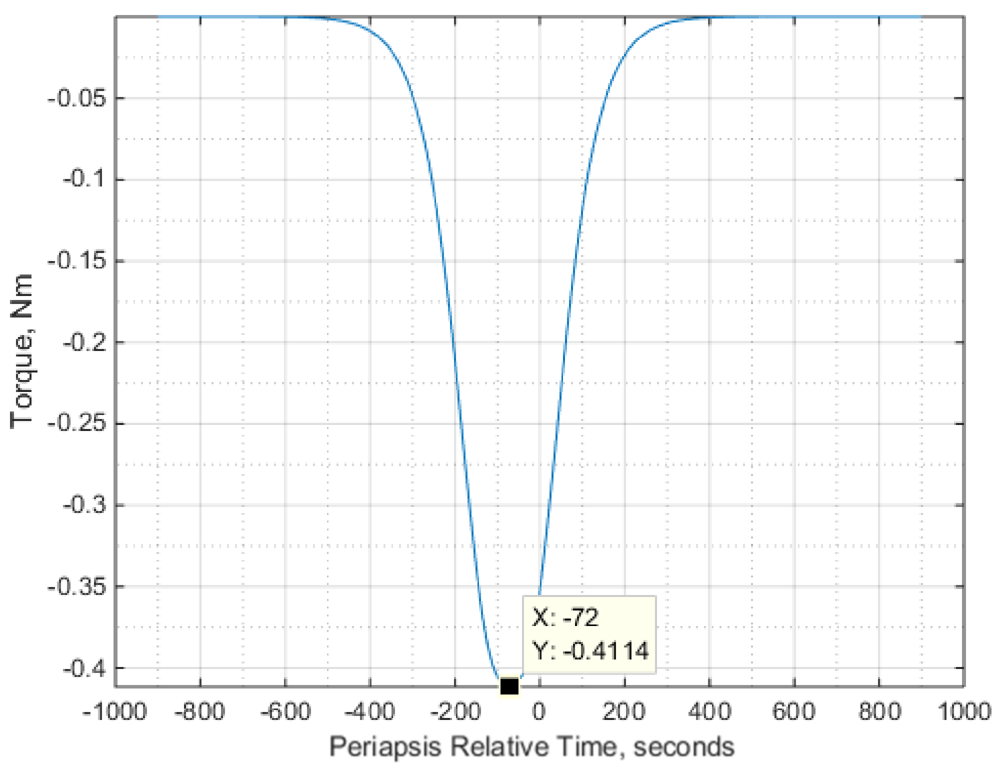

Figure 5. Rev-288 atmospheric torque about S/C Z-axis

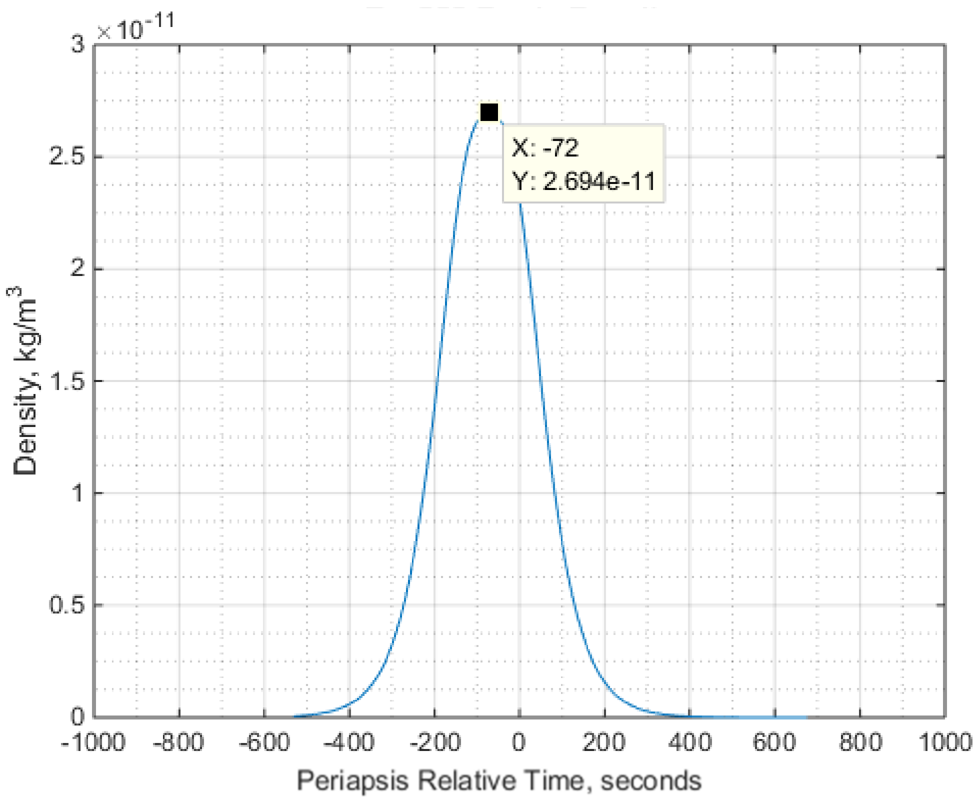

Figure 6. Rev-288 density profile resulting from "thruster on-time reconstruction" method

V. Saturn Density Reconstruction Results For Five Final Orbits of Cassini Mission

A. Reconstruction Results using Thruster On-Time Flight Data

Using the thruster on-time reconstruction method outlined above, density profiles for each of the five final orbits (Rev-288 through Rev-292) have been reconstructed, and are provided below. Additionally, thruster duty cycle profiles for each orbit have also been constructed. Note that the duty cycle profiles have been smoothed via local regression using weighted linear least squares and a 2nd degree polynomial model. Altitude profiles have also been provided. Unlike the density and duty cycle plots which depend on thruster attitude control flight data, the altitude plots are reconstructed using the Navigation team's radiometric tracking data. Table 3 summarizes key parameters for each of the five final orbits.

Table 3. Summary of Final Five Orbits (Rev288-Rev292)

Rev	Periapsis Date	Periapsis Time SCET	Y-Thrusters %	Z-Thrusters %	Minimum Altitude km	Peak Density kg/m^3
288	14 August 2017	226T04:23:02	29.7	10.9	1706	2.6939e-11
289	20 August 2017	232T15:23:00	33.3	44.0	1652	3.4097e-11
290	27 August 2017	239T02:18:10	40.6	15.0	1626	3.6244e-11
291	2 September 2017	245T13:13:00	41.0	14.5	1639	3.6267e-11
292	9 September 2017	252T00:09:44	25.8	9.5	1675	2.3722e-11

The table above summarizes the results of the Saturn atmospheric density reconstructions, using thruster on-time data. The reconstruction process is derived from the Titan atmospheric density reconstruction method developed in references 5 and 8.

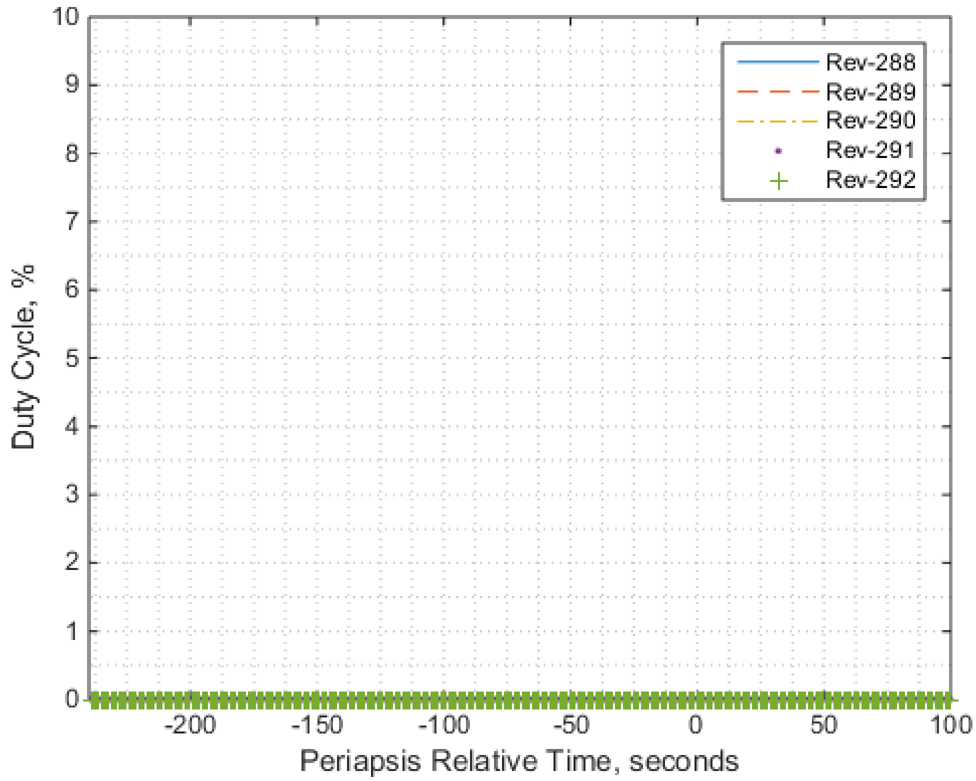

Figure 7. Smoothed duty cycle profiles for the Y1/Y3 thruster pair

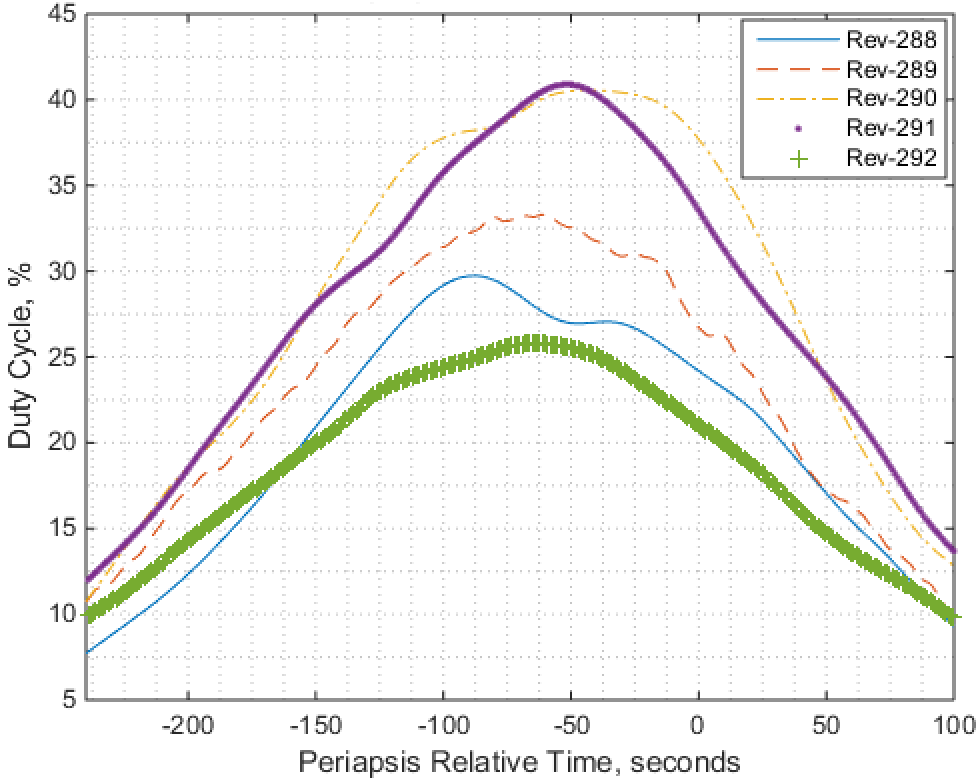

Figure 8. Smoothed duty cycle profiles for the Y2/Y4 thruster pair

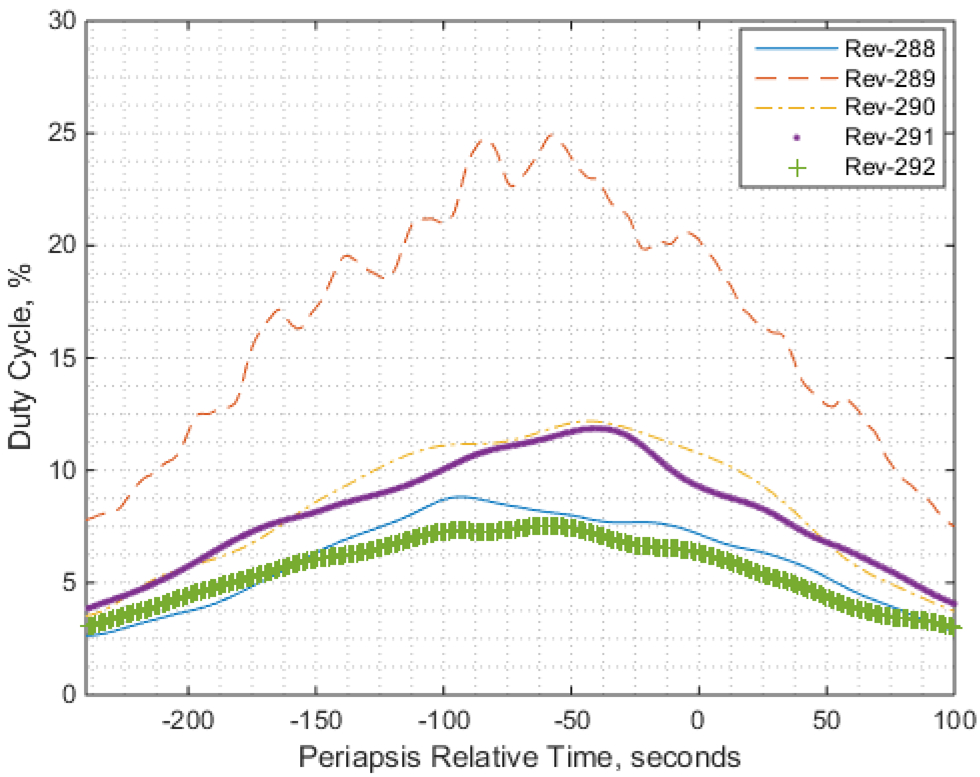

Figure 9. Smoothed duty cycle profiles for the Z1 thruster

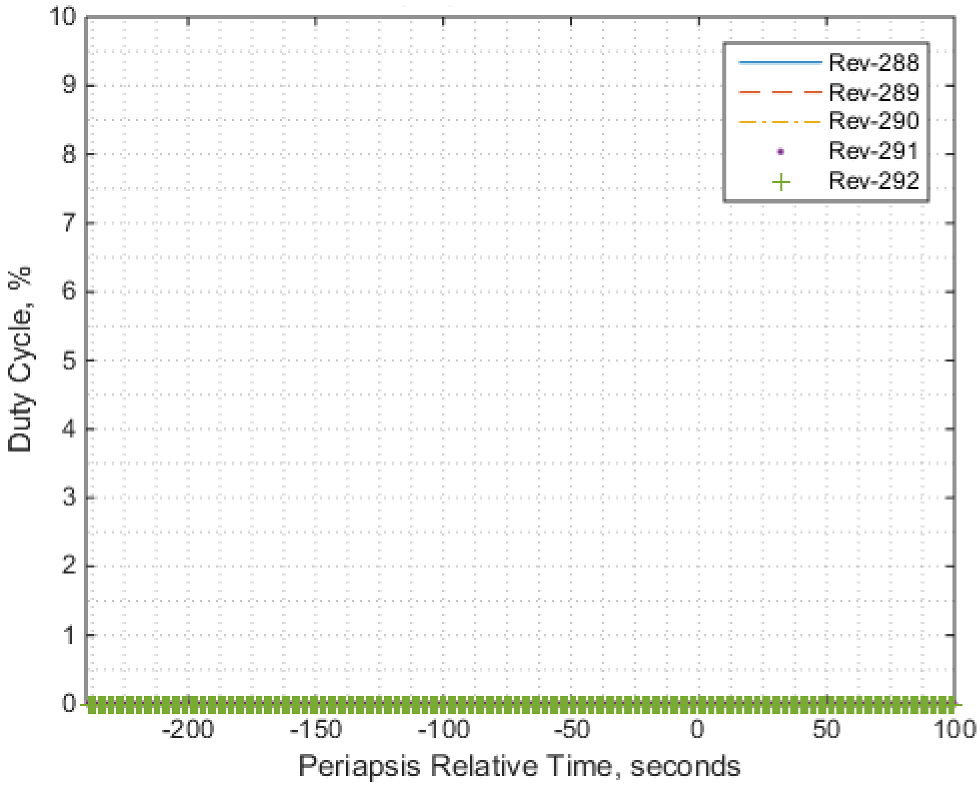

Figure 10. Smoothed duty cycle profiles for the Z2 thruster

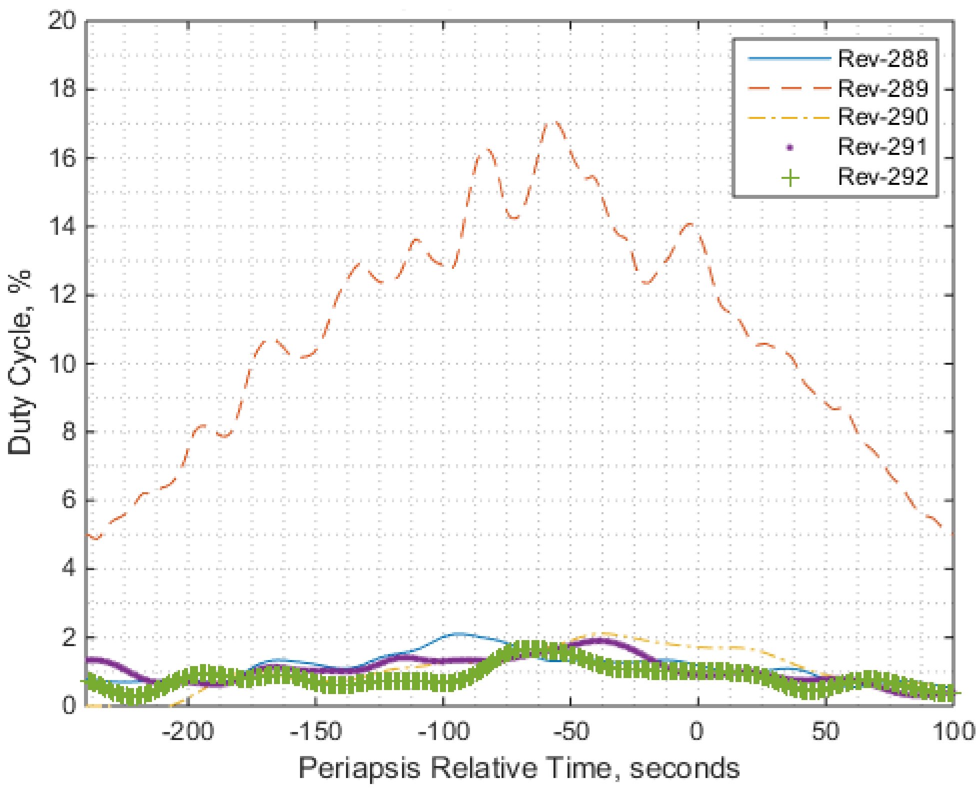

Figure 11. Smoothed duty cycle profiles for the Z3 thruster

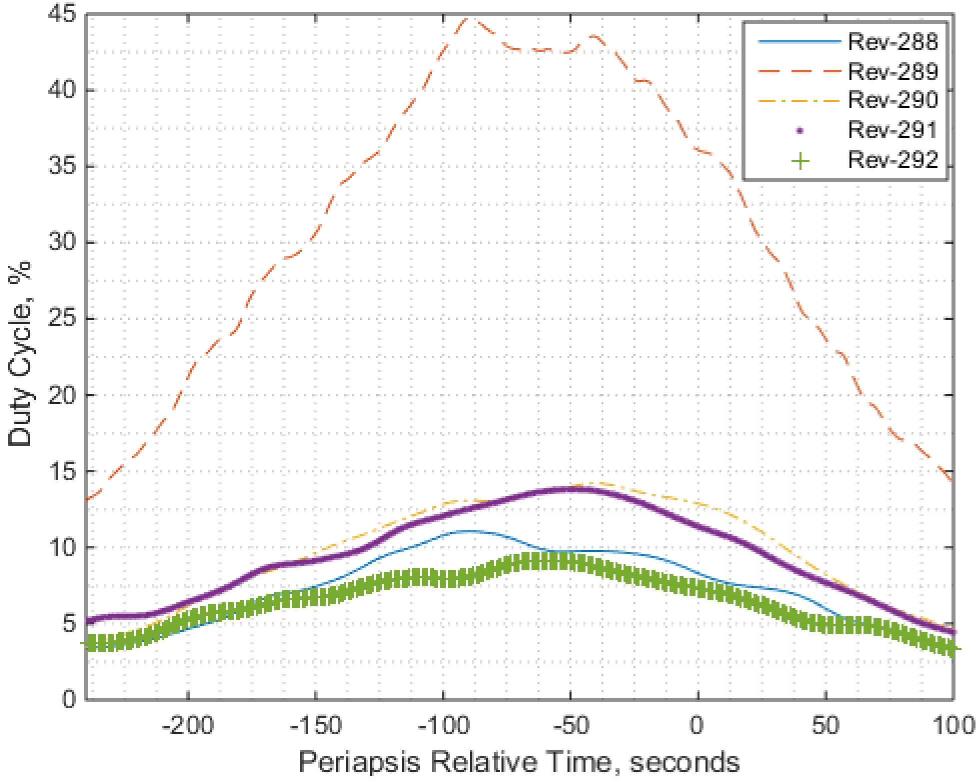

Figure 12. Smoothed duty cycle profiles for the Z4 thruster

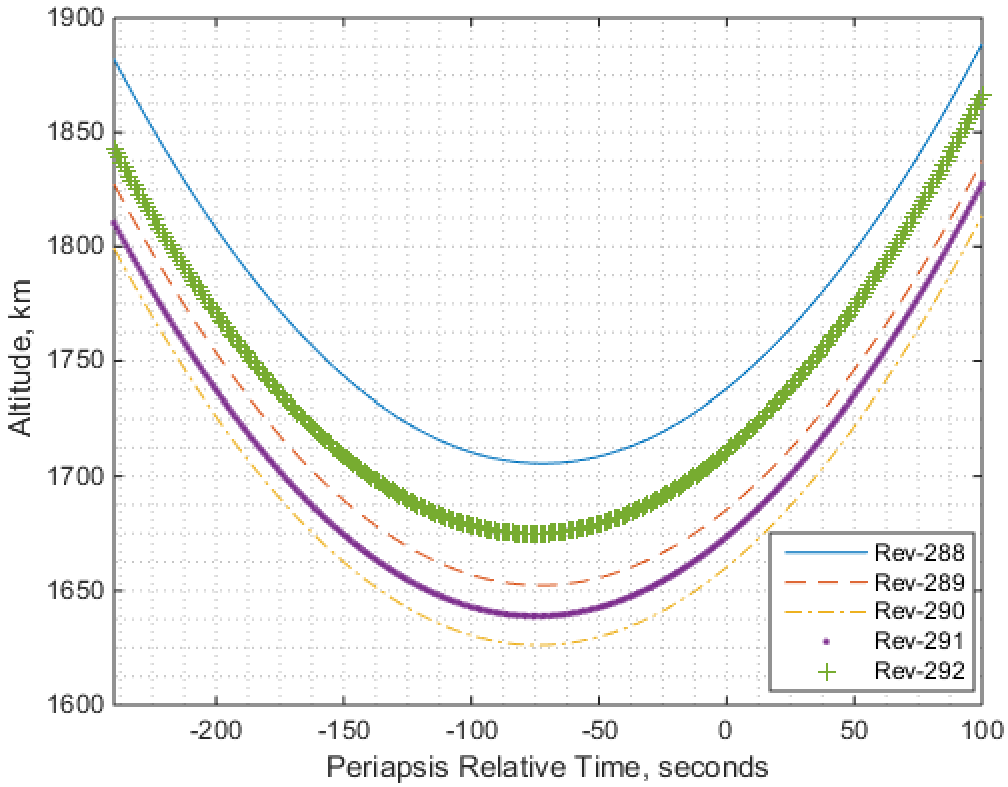

Figure 13. Flyby altitude profiles reconstructed from navigation radiometric tracking data

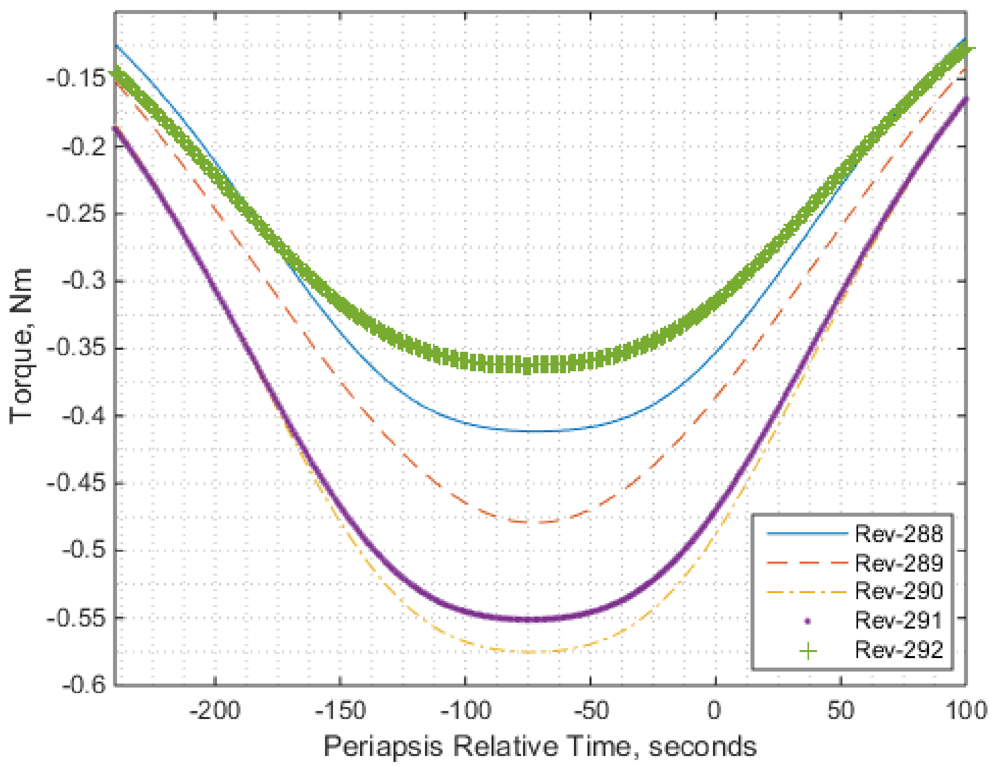

Figure 14. Atmospheric torque profiles reconstructed about the S/C Z-body axis

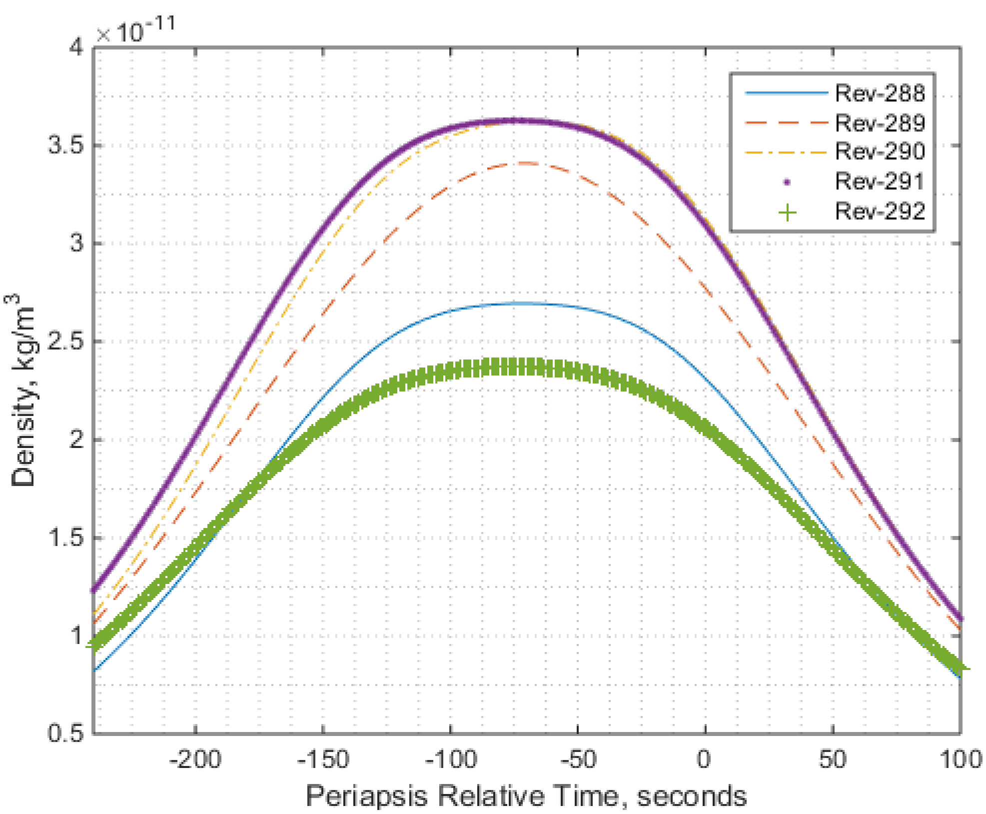

Figure 15. Atmospheric density profiles for Rev288-292 reconstructed about the S/C Z-body axis

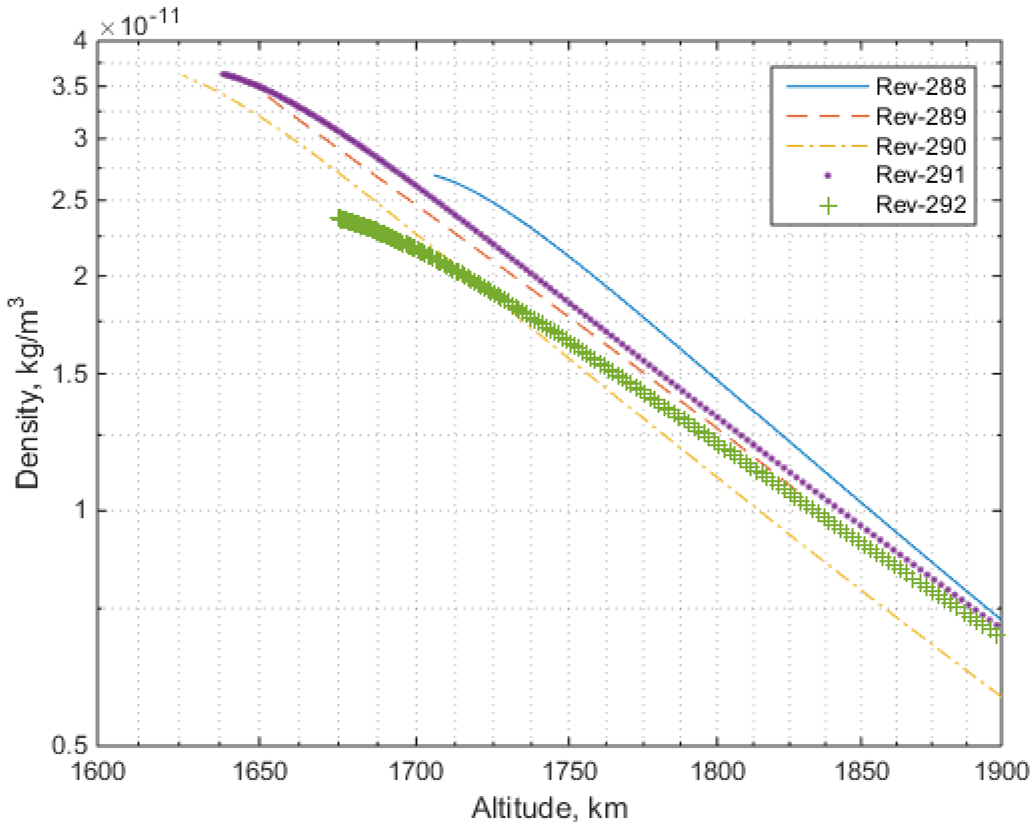

Figure 16. Inbound atmospheric density vs. altitude for Rev288-292 reconstructed about the S/C Z-body axis

B. Variations in Thruster Duty Cycle Profiles

The thruster duty cycles are dependent on the orientation of the spacecraft as it flys through the atmosphere, since the orientation will determine the effective "moment arm" between the center of mass and the center of pressure. All five orbit periapses were flown with orientations that kept the duty cycles for the Y1/Y3 thruster pair and the Z2 thruster at ~0% as shown in Figs. 7 and 10. Rev-289 had a different orientation (for science purposes) compared to the other four Saturn-skimming orbits. This different orientation increased the CP-CM moment arm, resulting in larger duty cycles for the Z1, Z3, and Z4 thrusters as shown in Figs. 9, 11, and 12. Appendix A presents the orientation flown at periapsis for each of the final five orbits (Rev-288 through Rev-292).

VI. Final Plunge Duty Cycle Profiles and Predicted Density Profile

The density reconstruction method outlined in this paper cannot be applied to Cassini's September 15 final plunge because the method requires outbound data to satisfy the inherent symmetry of the hyperbolic tangent curve-fitting functions. However, the inbound thruster on-time data can still be used to construct duty cycle profiles relative to the time of "loss of signal" (LOS). LOS (X-Band Telemetry) for the Cassini spacecraft was at 258T10:31:51.00 SCET {11:55:18:00 ERT(UTC)}. Additionally, the in-situ data that was sampled during Rev-288 through Rev-292 gave the Cassini team insight into the composition and density of the Saturnian atmosphere. This flight data was used to update the atmosphere models and obtain an improved prediction of the atmospheric profile that the spacecraft should expect during the final plunge. Table 4 presents the best altitude and atmospheric density predictions the Cassini team had before the plunge. Figure 17 reports duty cycle profiles from real thruster flight data using a 1-second window for each calculation. Note that only the Z4 thruster and the Y2/Y4 thruster pair are included, because these were the thrusters that reached 100% duty cycle. In other words, the atmospheric torque imposed on the spacecraft during the plunge pushed these three thruster to their limit and once they reached 100% duty cycle, the spacecraft began to tumble. Figures 18 through 21 plot the plunge atmospheric predicts from Table 4.

Table 4. Atmospheric Density and Altitude Predicts Prior to the Final Plunge

SCET	Altitude km	Density kg/m^3	Radius from Saturn Center km
2017-258T10:31:28.000	1546.850	5.6695865e-11	61597.542
2017-258T10:31:29.000	1540.144	5.8892472e-11	61592.076
2017-258T10:31:30.000	1533.450	6.1171994e-11	61586.620
2017-258T10:31:31.000	1526.767	6.3537583e-11	61581.171
2017-258T10:31:32.000	1520.095	6.5992520e-11	61575.731
2017-258T10:31:33.000	1513.434	6.8540230e-11	61570.300
2017-258T10:31:34.000	1506.785	7.1184284e-11	61564.877
2017-258T10:31:35.000	1500.147	7.3928410e-11	61559.463
2017-258T10:31:36.000	1493.520	7.6776504e-11	61554.058
2017-258T10:31:37.000	1486.904	7.9732637e-11	61548.660
2017-258T10:31:38.000	1480.300	8.2801068e-11	61543.272
2017-258T10:31:39.000	1473.708	8.5986254e-11	61537.892
2017-258T10:31:40.000	1467.126	8.9292866e-11	61532.520
2017-258T10:31:41.000	1460.556	9.2725801e-11	61527.157
2017-258T10:31:42.000	1453.997	9.6290194e-11	61521.803
2017-258T10:31:43.000	1447.450	9.9991443e-11	61516.457
2017-258T10:31:44.000	1440.914	1.0383522e-10	61511.120
2017-258T10:31:45.000	1434.390	1.0782749e-10	61505.791
2017-258T10:31:46.000	1427.877	1.1197453e-10	61500.471
2017-258T10:31:47.000	1421.375	1.1628297e-10	61495.159
2017-258T10:31:48.000	1414.885	1.2075981e-10	61489.856
2017-258T10:31:49.000	1408.406	1.2541241e-10	61484.562
2017-258T10:31:50.000	1401.938	1.3024860e-10	61479.276

The table above summarizes the best predicts the Cassini team had of the density and altitude of the final plunge after updating the atmosphere models with the in-situ measurements taken during Rev-288 through Rev-292.

VII. Conclusion

The final five full orbits of the Cassini spacecraft (Rev-288 through Rev-292) and the final plunge have given scientists and engineers their first and only in-situ measurements of Saturn's atmosphere in the history of human and robotic space exploration. The Cassini-Huygens Mission to Saturn has been one of humanity's greatest endeavors and its success has paved the way for future missions to continue exploring the Saturnian system. The purpose of this analysis was to propose a method of atmospheric density reconstruction based on attitude control flight data, and to apply that method to obtain density as a function of time and altitude for Rev-288 through Rev-292. One possible area of future work would be to try to enhance the proposed reconstruction method by reducing the uncertainity in the center of pressure parameter that feeds into Eq. (3). A similar endeavor was attempted in Ref. 6. Another area of future work would be to modify the reconstruction method to be able to reconstruct the final plunge density profile. In order to do this, the hyperbolic tangent curve-fitting functions would have to be replaced by more suitable functions. Additionally, the method would have to be modified to account for the fact that during the last few seconds of the final plunge, the thrusters were at 100% duty cycle and were being overwhelmed by the atmospheric torque. The current reconstruction method assumes the thrusters are able to maintain full control authority, i.e. that all of the accumulated angular momentum is being absorbed by the thrusters. Finally, it would be of great benefit to compare the results presented in this paper with results obtained by the other independent methods as discussed in section IV.

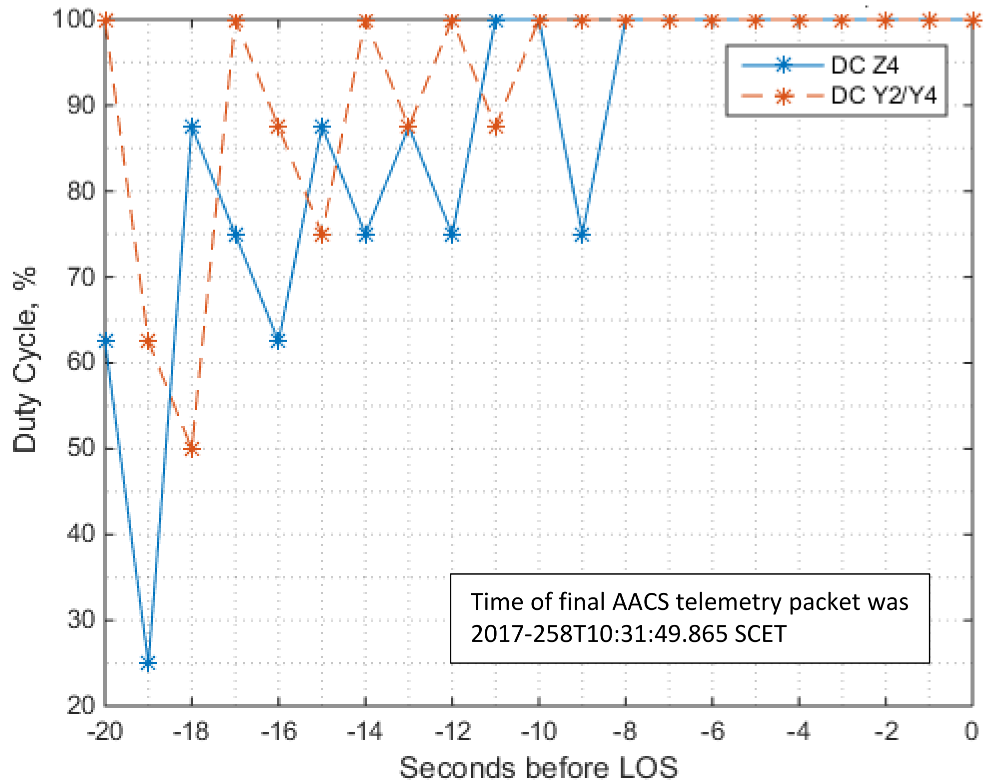

Figure 17. Z4 and Y2/Y4 thruster duty cycles (from flight data) for the last 20 seconds before LOS

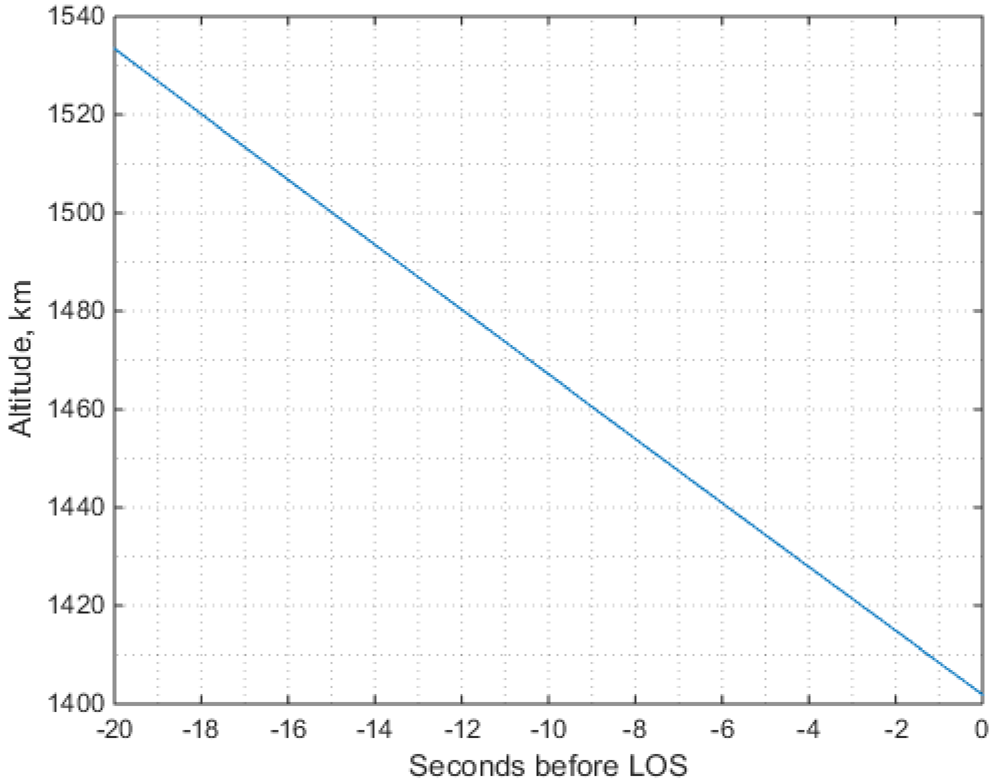

Figure 18. Predicted altitude during plunge

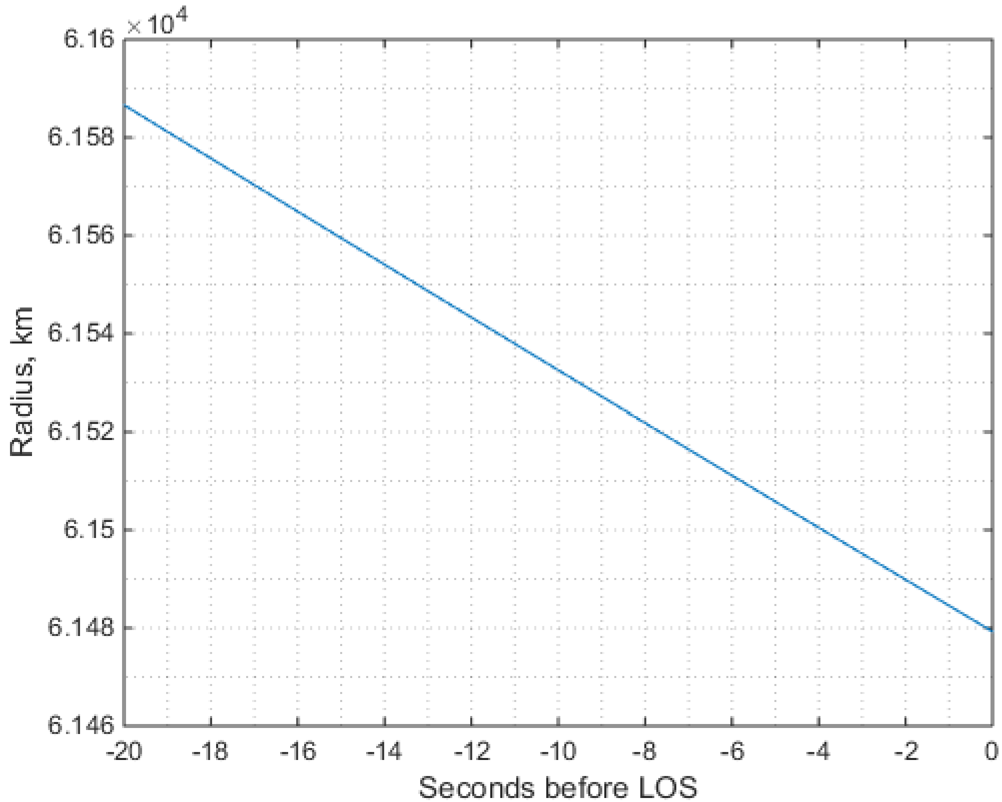

Figure 19. Predicted radius from Saturn center during plunge

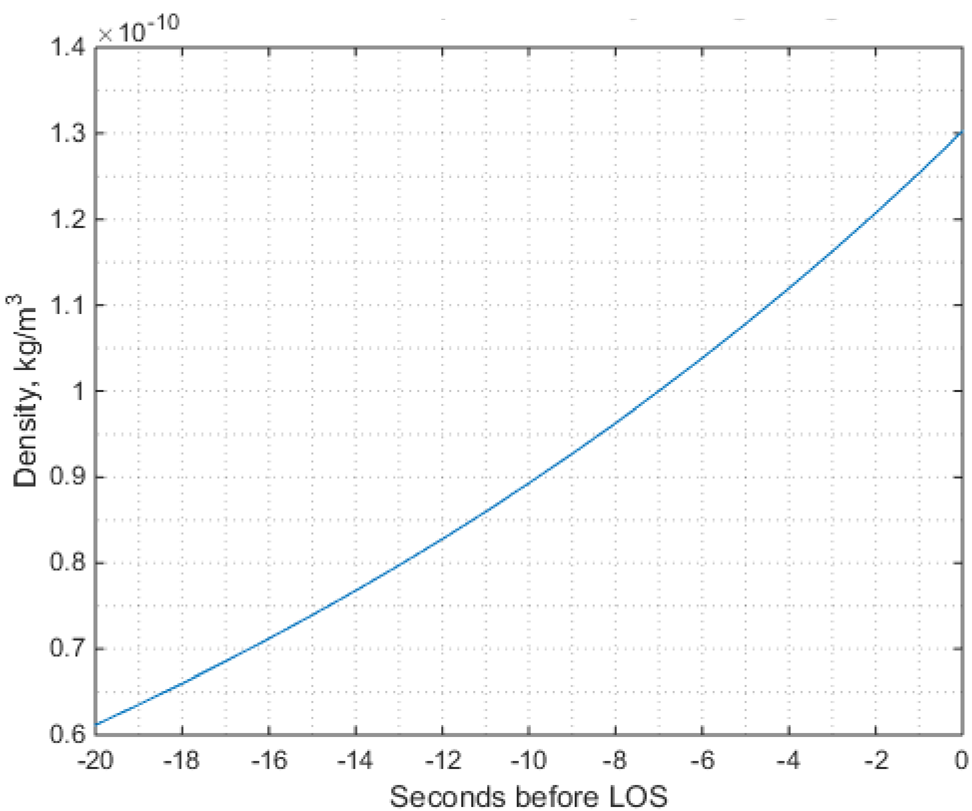

Figure 20. Predicted atmospheric density during plunge

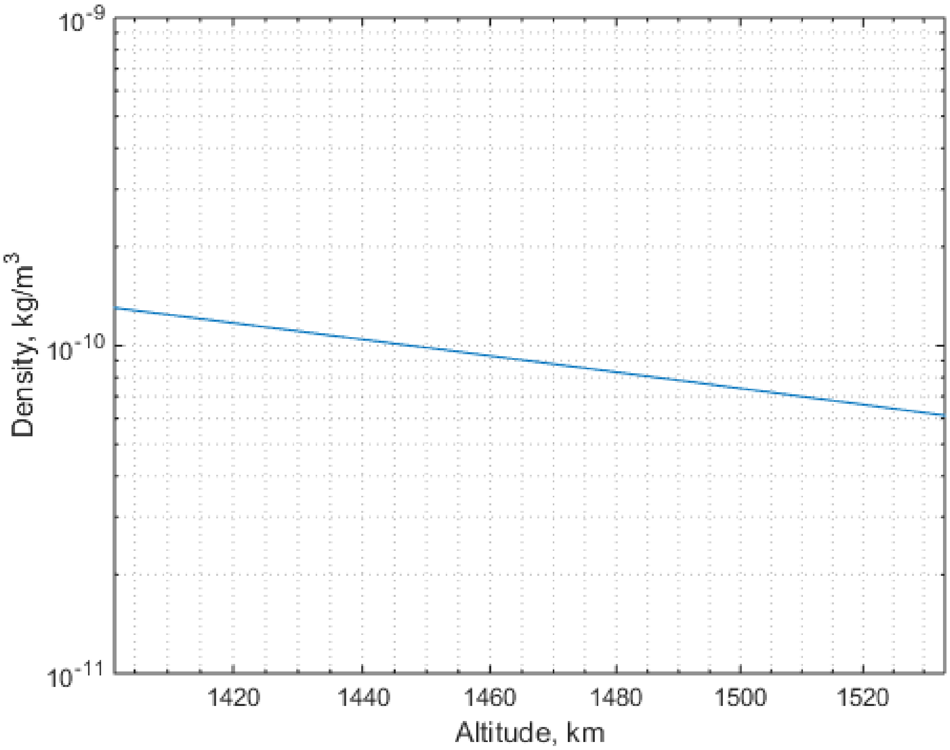

Figure 21. Predicted atmospheric density vs. altitude during plunge

Appendix A

Appendix A provides diagrams of the spacecraft orientation flown at periapsis for each of the five final orbits (Rev-288 through Rev-292). The reader's point of view is aligned with the oncoming flow of Saturn atmosphere particles. In other words, the reader can imagine that the flow of Saturn atmosphere particles hitting the spacecraft is going into the page. The figures were courtesy of Erick Sturm of the Cassini Mission Planning team.

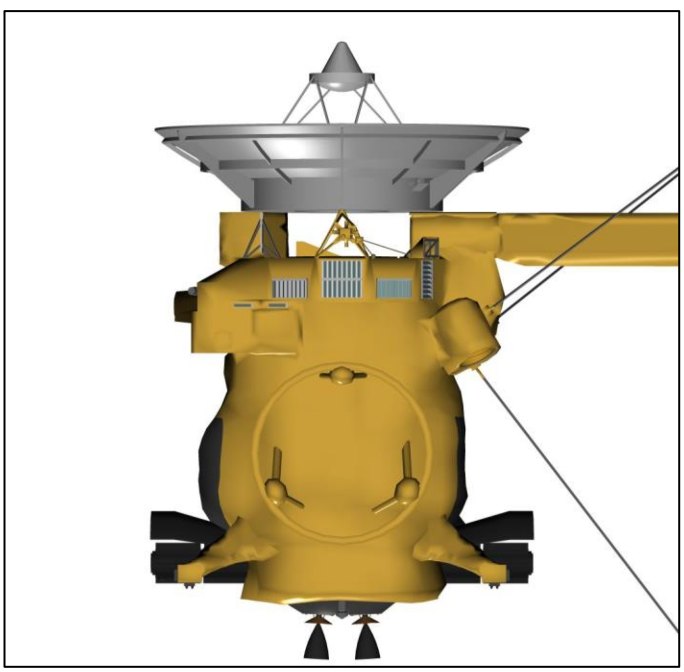

Figure A1. Rev-288 spacecraft orientation at periapsis

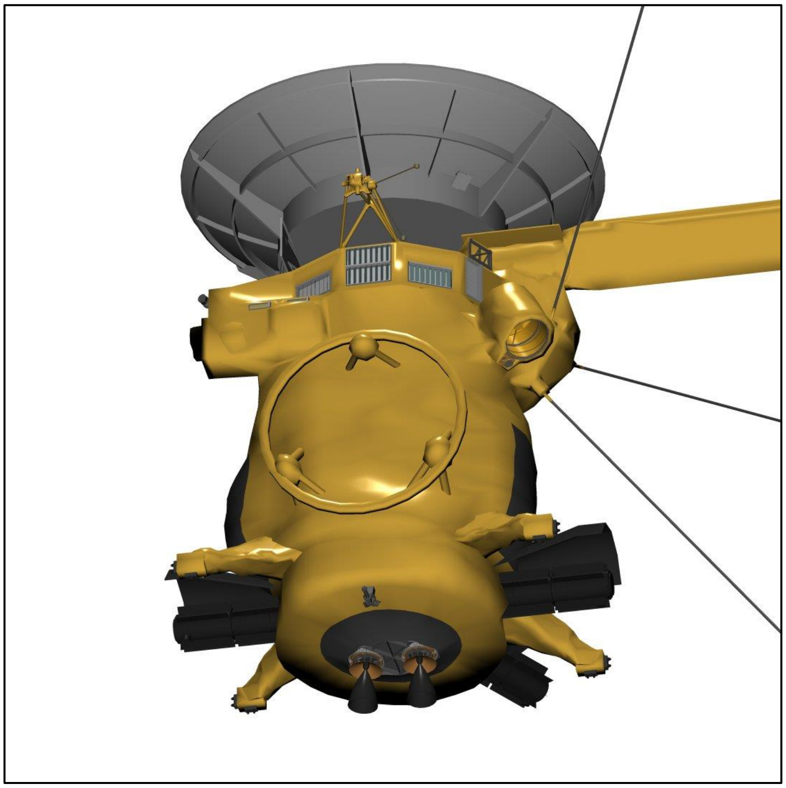

Figure A2. Rev-289 spacecraft orientation at periapsis

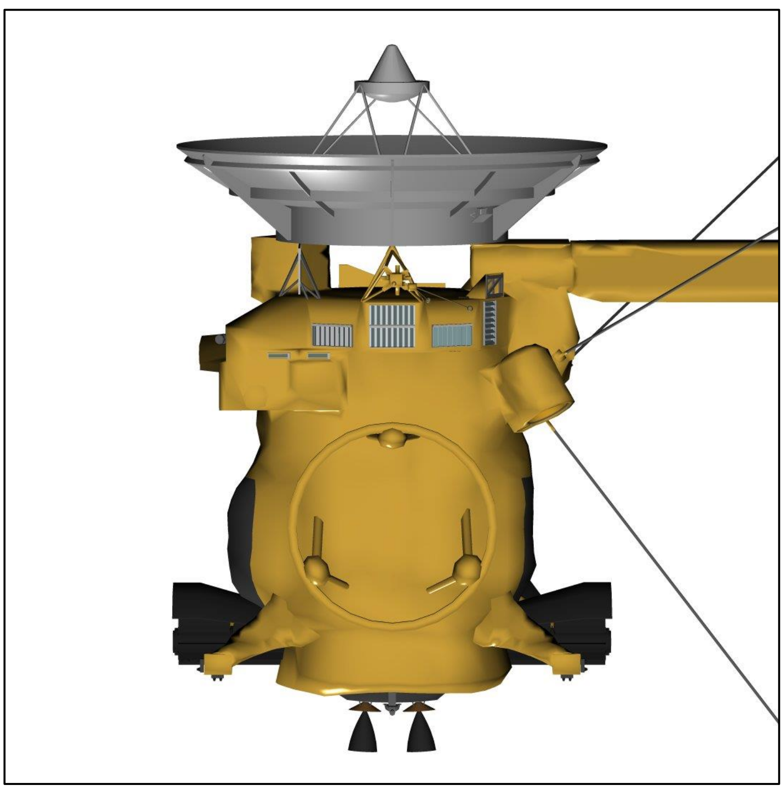

Figure A3. Rev-290 spacecraft orientation at periapsis

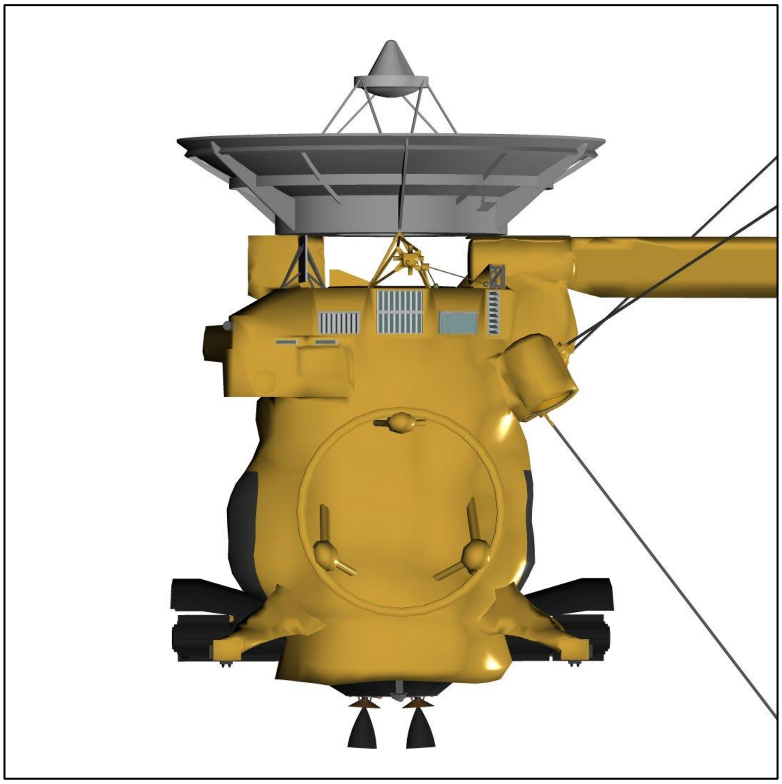

Figure A4. Rev-291 spacecraft orientation at periapsis

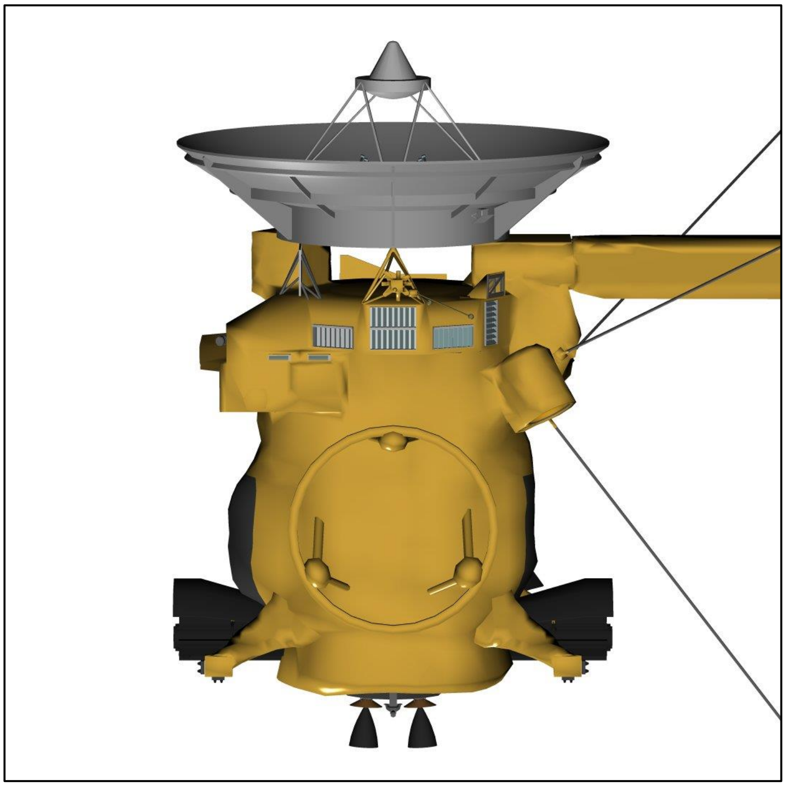

Figure A5. Rev-292 spacecraft orientation at periapsis

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